Project Report: The Planetary Context of Biological Evolution: Neoproterozoic−Cambrian Environmental Change and Evolution

Lead Team:	***Harvard University***
Project Title:	***The Planetary Context of Biological Evolution: Neoproterozoic−Cambrian Environmental Change and Evolution***
Project Investigator:	***Andrew Knoll***

Project Progress

Subproject 2, Neoproterozoic−Cambrian environmental change and evolution, has enjoyed the broadest participation of Harvard team members, and for good reason. The Proterozoic−Cambrian transition witnessed remarkable changes in tectonics, climate, atmospheric composition, and especially life. This is the interval during which animal life −− and, hence, the prospect of intelligence, radiated on Earth. Harvard team researchers are studying the paleontology (Knoll, Grotzinger, Erwin), geochronology (Bowring, Grotzinger), tectonics (Hoffman, Bowring), and environmental changes (Hoffman, Schrag, Bowring, Grotzinger) of this interval, with an eye to constructing models of integrated change in the Earth system. Specific progress in Year 4 includes the following:

1. In Newfoundland, Sam Bowring has dated thin volcanic ash beds below, within, and above the Gaskiers glacial deposits. The bottom line is that from 8 meters below the glacial deposits to 10 meters above, the ages are within error of one another and cluster near 580 Ma. These are the first high−precision temporal constraints on the age and duration of a Neoproterozoic glaciation. The oldest Edaicarans known from the rock record lie approximately 100−200 meters above the glacials and are 575 Ma, leaving approximately 5 Ma between the last glacial deposit and the first expansion of macroscopic metazoans.
2. The dramatic diversification of animal phyla during early Cambrian time has fueled debate regarding the mechanisms of early animal evolution for over a century. What is now clear is that intrinsic catalysts, such as the innovation of developmental genetic mechanisms, as well as extrinsic processes, involving environmental change, are both critically important in accounting for this major event in the history of life. Recent attempts to delineate potential extrinsic factors have revealed a large−magnitude but short−lived negative excursion in the

carbon−isotopic of seawater that is globally coincident with the Precambrian−Cambrian boundary. Possible mass extinction, in some manner related to this negative isotope excursion, has been invoked as a contributing mechanism that led to rapid diversification of metazoans within restructured early Cambrian ecosystems. Research by John Grotzinger and Sam Bowring on biostratigraphic, carbon isotopic, trace element, and uranium−lead zircon geochronological data from Oman supports this hypothesis, indicating an extinction of terminal Proterozoic calcified metazoans coincident with this boundary isotope excursion ca 542 Ma. The age in Oman is within error of age of the boundary in Namibia and Siberia, confirming the global synchroneity of this event.

3. In continuing field research in Namibia, Grotzinger has discovered a new type of skeletonized animal fossil in latest Proterozoic reefs. The new fossils are colonial cnidarian−like organisms that lived in cryptic environments within cracks in the reef edifice.
4. Erwin has been investigating new findings from molecular development, with an eye for their application to understanding early animal evolution. He finds that developmental data have been overinterpreted, with ancestral bilaterians less morphologically complex than claimed. A paper completed with molecular biologist Eric Davidson explores the consequences of this finding for our thinking about early animal diversification.
5. Paul Hoffman continues to explore the theory, phenomenology and consequences of Snowball glaciation on the late Proterozoic Earth. Hoffman's continuing field programs focus on the geology and isotopic records of carbonate successions in Namibia, Svalbard, Morocco and Canada, that together span the critical time interval from around 850 to 530 Ma (mid−Neoproterozoic through to the Cambrian ?explosion?). This interval includes three glacial episodes with unusual features that form the basis for the ?snowball earth? hypothesis. Three new tests of the hypothesis are currently under way:

   i.) A geochemical search for interplanetary dust, which predictably should have accumulated on the global ice shell: The search is targeted at a newly discovered clay layer that separates the glacial deposits from post−glacial cap carbonate. Platinum group elements are being analyzed in collaboration with Cin−Ty Lee at Rice University.
   ii.) A study of boron isotopes before and after glaciation, when seawater pH is predicted to be abnormally high and low, respectively: Boron hydrate speciation in seawater is pH sensitive and fractionated with respect to boron isotopes. This approach has previously been applied to Cenozoic carbonates only, and no Proterozoic boron isotope base level is established. The work will be done in collaboration with Stan Hart at Woods Hole Oceanographic Institution.
   iii.) An oxygen, sulfur and strontium isotopic study of primary barite seafloor cements discovered in post−glacial cap carbonates: Sea−floor barite ($BaSO_4$) is extraordinary but may be a predictable consequence of an unusually stable density stratification when sulfidic deep water evolved beneath a global ice shell is capped by an oxic surface layer dominated by melt water. The isotopic work will be done collaboratively

with Dan Schrag at Harvard.

6. The research program of Daniel Schrag covers a wide range of geochemical problems aimed at describing the climate history over a wide range of time scales, and using geochemical tools to understand how geochemical cycles interact with ecosystems. As part of the Harvard Astrobiology group, he is working with Hoffman on geochemical studies and models of Neoproerozoic glaciation. In addition, Schrag has started a new project developing the oxygen isotopic composition of marine barite as a measure of the oxygen isotopic composition of seawater through the history of the Earth. He will use this new tool to test hypotheses regarding the effects of the evolution of biomineralization on marine chemistry. Previous work by Schrag and others have demonstrated that carbon isotope measurements of dissolved inorganic carbon in deep sea pore fluids can be used to measure the metabolic activity of bacteria in deep sea sediments. In the past year, he has been collaborating with colleagues at the University of Rhode Island as part of the Ocean Drilling Program's Leg 201, a cruise specifically devoted to studying microbial activity in deep sea sediments. This past spring, scientists collected over 500 samples of deep sea pore fluids for analysis. The samples are currently being measured, and we expect results later this summer. These results will be particularly exciting, as they will be part of a suite of measurements on these cores including genetic work and a wide variety of organic chemistry.

   Over the past year, Schrag has made substantial progress working through geochemical models of two important aspects of the Snowball Earth hypothesis. First, in collaboration with Bob Berner at Yale, we studied what might have caused the global glaciation in the first place. This paper has just been published in *Geochemistry, Geophysics, Geosystems* (Schrag et al., 2002). It suggests that a tropical concentration of continental area may play a critical role in triggering the onset of a global glaciation, both through its effects on continental weathering as well as encouraging organic carbon burial in tropical river deltas. The presence of a large negative carbon isotope anomaly just before the glaciation suggests that methane may play a role in the snowball earth phenomena. This idea is discussed, and a novel hypothesis is presented through which the release of methane from sediments may actually cause the glaciation through its interaction with silicate weathering.

   A long−standing controversy in the geochemical community is whether the oxygen isotope composition of the ocean has changed significantly during the history of the Earth. Based on oxygen isotopic measurements in well preserved carbonates, cherts, and phosphates, it appears that the $d^{18}O$ of the ocean was isotopically depleted by 7? in the Proterozoic epoch and has been increasing to today's value of 0? through the Phanerozoic period. Schrag and colleagues have developed a new hypothesis that the reason for this change may involve the evolution of biomineralization of calcium carbonate during the early Phanerozoic. To test this idea, Schrag has initiated a series of modeling studies and, in addition, is working on using marine barite (barium sulfate) to measure the oxygen isotopic composition of seawater through time. Barite is extremely resistant to diagenetic alteration, making it better suited for isotopic measurements over longer periods of time. He expects that these results will elucidate how the biomineralization of calcium carbonate can affect various biogeochemical cycles, and might be detectable on other planets.

7. Knoll's group continues to document the fossil record of protists and animals near the Proterozoic−Cambrian boundary. Two monographs were completed during the past year, one on Burgess Shale−type compressions that document in exquisite detail the morphological diversity of multicellular organisms just before the Ediacaran radiation, and a second on testate amoebae in 750 Ma rocks from the Grand Canyon, providing our oldest ecologically and taxonomically clear view of heterotrophic eukaryotes in the fossil record. A collaborative project with Francis Albarede in Lyon, France, has yielded a Pb−Pb age for Doushantuop phosphates of 598+/−2 million years; these rocks contain the oldest known (microscopic) remains of animals.

Highlights

- Harvard team members have documented heterotrophic protists, diverse multicellular algae, possible primitive animals, and early cnidarian−like colonies with skeletons in Neoproterozoic rocks from China, Namibia and North America. Such fossils tie evolutionary inference from molecular phylogenies ever more closely to Earth's physical history.

- Team members have also provided new age constraints on Neoproterozoic ice ages and early animal evolution, further tying molecular inferences to Earth history through time calibration.

- Team members have developed new insights into the origin, duration and consequences of extreme glaciation during the Neoproterozoic Era.

Roadmap Objectives

- ***Objective No. 4:*** Genomic Clues to Evolution
- ***Objective No. 5:*** Linking Planetary Biological Evolution
- ***Objective No. 8:*** Past Present Life on Mars
- ***Objective No. 12:*** Effects of Climate Geology on Habitability
- ***Objective No. 14:*** Ecosystem Response to Rapid Environmental Change

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****

3	High resolution field mapping on Mars	Developing digital mapping tehniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The digital mapping techniques under development by Grotzinger will be applicable to any serious investigation of Martian geology undertaken in lander expeditions in 2009 and beyond. Understanding the physical environmental of Earth during, before, and after snowball glaciation is also immediately relevant to the astrobiological characterization of extrasolar planets, currently under development by NASA.

Field Expeditions

Field Trip Name: Namibia Snowball glaciation	
Start Date: 06/10/2002	***End Date:*** 07/10/2002
Continent: Africa	***Country:*** Namibia
State/Province:	***Nearest City/Town:*** Luederitz
Latitude: 28 N	***Longitude:*** 16 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Field mapping and sequence stratigraphy of Neoproterozoic tillite−bearing successions; collections for geochronology and geochemistry	
Members Involved: P.F. Hoffman lab	

Field Trip Name: Neoproterozoic stratigraphy in Svalbard	
Start Date: 07/22/2001	***End Date:*** 08/17/2001
Continent: Europe	***Country:*** Norway

State/Province: Svalbard	***Nearest City/Town:*** Longyearbyen
Latitude: 28 N	***Longitude:*** 16 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Field mapping and sequence stratigraphy of Neoproterozoic successions; collections for geochemistry and petrology	
Members Involved: P.F. Hoffman lab	

Field Trip Name: China	
Start Date: 03/27/2002	***End Date:*** 04/05/2002
Continent: Asia	***Country:*** China
State/Province: Yunnan	***Nearest City/Town:*** Kunming
Latitude: 25 N	***Longitude:*** 105 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collect samples for calibrating the Cambrian Explosion	
Members Involved: S. Bowring	

Field Trip Name: Newfoundland	
Start Date: 08/01/2001	***End Date:*** 08/28/2001
Continent: North America	***Country:*** Canada
State/Province: Newfoundland	***Nearest City/Town:*** St. John's
Latitude: 48 N	***Longitude:*** 53 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collect samples for calibrating the Neoprotrozoic glacial succession	
Members Involved: Sam Bowring	

Field Trip Name: Namibia terminal Proterozoic stratigraphy and paleontology

Start Date: 05/25/2002	***End Date:*** 07/10/2002
Continent: Africa	***Country:*** Namibia
State/Province:	***Nearest City/Town:*** Rehoboth
Latitude: 23 N	***Longitude:*** 16 E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Field mapping of terminal Proterozoic reefs; collection of samples for petrology, geochemistry, geochronology and paleontology	
Members Involved: J.P. Grotzinger	